Supporting information

Teaching and assessing systems thinking in first-year chemistry

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Rater Training Manual

The purpose of this manual is to prepare and guide raters to assess System Oriented Concept Mapping extensions, which are extended concept maps focused on visualizing the complex interconnections between different subsystems in a system under consideration. The system considered for these practical activities was based on the role and real-world implications that an anionic surfactant, Linear Alkylbenzene Sulfonate (LAS), commonly used in laundry detergents has in the environmental, societal, and economic subsystems. It is recommended that raters work through the resources, which include the quizzes, practical activities, and videos of the systems thinking activities to understand the context of the activities before assessing SOCMEs. The rubric was designed from the Structure of Observed Learning Outcomes (SOLO taxonomy) to assess systems thinking skills demonstrated in SOCME diagrams. Before using the manual, it is recommended to read through the terminology (Table 1) first to understand common terms used in the teaching and assessment of systems thinking.

Table 1: Terminology

1.1 Terminology for systems thinking

Term	Description
System	A structure containing interconnected parts whose behavior is not explained by the properties of the parts alone. (Sabelli, 2006) The system functions as a whole through the interactions of its parts to fulfill a purpose in the presence of its parts. (Assaraf & Orion, 2005)
Subsystems	Smaller collections of interconnected parts that form a subset of the larger system that are distinct from each other, but that still play a role in the larger system. (Kramer, 1977)
Subsystem boundary	Boundaries that show the distinctness of each subsystem from the larger system and other subsystems while recognizing their interconnections. (Becvar & Becvar, 2017)
Cyclic Behavior	Repeating patterns in the behavior of the system that can be represented with linear or non-linear cause and effect relationships or feedback loops (positive and negative processes). (Sweeney & Sterman, 2000)
Dynamic behavior	The behavior of a system that changes over time to understand past and future factors that have influenced system-level behavior (Richmond, 1997)
Emergent behavior	The process of a system to form new collective properties from the coherent behavior of interacting parts. (Barile & Saviano, 2011) These properties cannot be predicted from studying the properties of the parts. (Hammond, 1998)
Analysis	Breaking the whole its constituent parts that make up the system and its characteristics and detecting how the parts relate to one another. (Gogus, 2012; Orgill, York, & MacKellar, 2019)

Synthesis/Integration	The term synthesis derived from Greek etymology means putting together and joining the parts of a whole (Barile & Saviano, 2011). However, to avoid confusion in chemistry, we used the term integration instead to convey the same meaning.
Systems Thinking	The ability to use both analysis and integration skills to understand and visualize the interconnectedness of a system under consideration with its dynamic and emerging behavior from a more holistic perspective.

1.2 Terminology for concept mapping

Term	Description
Concepts or elements	An idea in the form of one or two words placed in a block
Connection	Represented by an arrow that indicates a relationship between two concepts
Linking word	Words written on arrows to describe a connection or relationship between concepts
Proposition	Are units of meaning when two or more concepts are linked to create a meaningful sentence

1.3 Terminology for rubric based on the SOLO taxonomy

Term	Description
SOLO Taxonomy	The Structure of Observed Learning Outcomes taxonomy is a model that describes levels of increasing complexity in student's understanding
Levels in SOLO	Can either be pre-structural, unistructural, multistructural, relational, or extended abstract, each level is described in the rubric
Sublevel in SOLO	Can either be low, medium, or high as shown in the rubric

The following learning outcomes shown in **Table 2** on **page 3**, which are the systems thinking skills derived from the STH model and ChEMIST table, were identified for the systems thinking activities. The rubric is designed to assess some of these learning outcomes on SOCME diagrams, as not all the skills/attitudes can be assessed from a SOCME diagram. Therefore *analysis: elements, analysis: relationships, integration: dynamic interaction, integration: organization,* and *application* are assessed from students' efforts to expand the partial SOCME (Figure 1), shown on **page 4** that they were provided with in practical activity 2. A short rubric (Table 3) is provided on **page 5** to show the SOLO level alignment with the systems thinking skills and the assessment for grades in a nutshell. The full rubric is shown in Table 4 on **pages 6-8.** The possible new concepts and connections shown in Table 5 on **page 9** can provide an idea of what to expect from students' SOCMEs. However, it should be noticed that students' creativity should be welcomed and assessed based on its relevance and correctness to the system under consideration. Step-by-step instructions were given to support the use of the full rubric on pages **10-13**. The last section of the rater manual demonstrates how the stepwise flow chart can be used to assess an example SOCME and how the marks were awarded to grade the SOCME out of 80 on **pages 14-22.** A few recommendations can be read at the end of the manual on **page 22.**

Table 2: Assessing the quality of systems thinking skills demonstrated on SOCMEs

| ST skills	Alignment with LOs	Assessment of the skill on SOCME rubric	SOLO Level	Criteria	Quality
Chemistry understanding	LO1: Examine and understand molecular-level concepts and processes that influence system-level behaviour	The physical or chemical properties of surfactants	are not added to a SOCME as it is on a molecular level of granularity.		
Analysis: elements	LO2: Identify and illustrate the system-level concepts and processes relevant to a system	The newly added concepts w relevant to the system of LAS, which relate to any of the concepts learnt in the surfactant lecture.	unistructural and multistructural	Relevance	The new concepts added relate to the system of LAS and to the concepts learnt in the surfactant lecture regarding each subsystem
				Correctness	The concept is one to three words and does not contain a linking word
				Format	The concept is in a block with appropriate font size and colour
Analysis: relationships	LO3: Identify and illustrate the relationships between system-level concepts within subsystems	The connections and linking words made between concepts within and between the subsystems	relational low and medium level	Relevance	The connections and linking words added between concepts relate to the system of LAS
				Appropriateness	The linking words are appropriate and meaningful with enough information to describe the relationships between concepts
				Correctness	The linking words connects within or between subsystems as or both depending on the SOLO level
				Format	Linking words have right font size, on top or on arrows and arrows have heads and clearly connect concepts
				Propositions	Three or more concepts can be read as it follows onto each other. These can also include feedback loops where linking words describe how one concept influences another in both directions or in a cycle. The words increases, decreases can be used.
Integration: cyclic behaviour	LO4: Explain causes of cyclic behaviour and examine feedback loops in the system	Concepts and linking words added that indicated a cyclic behaviour or feedback loop (other than the biodegradation cycle and supply and demand cycle provided)	These skills were identified as too challenging for first-year students to demonstrate on their SOCMEs. They therefore engaged with feedback loops and emerging system behaviours given on the partial SOCME, and were not required to create their own. The outcomes were therefore not assessed by the SOCME rubric.		
Integration: emergence	LO5: Analyze potential emerging system-level behaviour in the system	Concepts and linking words were added that were factors that contribute to an emergent behaviour (foaming of LAS) in the system.			
Integration: dynamic interactions	LO6: Identify and describe interactions within and between subsystems that can change over time	Concepts and linking words were added between subsystems that could indicate changes in the system over time (dynamic behaviours)	Relational high level	Same as analysis: relationships	Same criteria as analysis: relationships. For dynamic interactions students can be prompted specifically to show which propositions can change over time within and between subsystems based on what they think are dynamic. Additional marks can be assigned here.
Integration: organization	LO7: Organize system-level concepts in the whole system and identify new subsystem boundaries	New concepts and link words fit into an appropriate subsystem and the addition of new subsystems (subsystem boundaries)	Extended abstract	Organization	The concepts and connections that have been added fit into the most appropriate subsystem as indicated with colours (example foaming fits in the environmental subsystem and is therefore colored in a green concept)
				Relevance	The new subsystem added with its concepts and connections are relevant to the system of LAS (for example agriculture subsystem could be relevant with good concepts and connections added)
Application	LO8: Predict factors that influence how a system changes over time	Concepts and linking words added to make predictions based on the options given (refer to quiz 2) and whether there is integration and interconnections shown throughout SOCME that tell a coherent story about LAS.	Extended abstract	Clear and relevant	The new predictions added are clear and relevant to the system of LAS or to content from the surfactant lesson
				Format	The predictions added have concepts and linking words in appropriate font size, blocks and arrows
				Propositions	The predictions can be read as concepts and linking words describe what can happened in the future. These added concepts are integrated throughout the system where connections and concepts are made within and between subsystems to describe the system.
Ownership	LO9: Consider the role of human activity on current and future system-level behaviour	Connection between surfactants and sustainability and the role of human action as an attitude	Attitude was not assessed in the SOCME rubric, but students reflected their intentions on taking ownership in the self-reflection questionnaire.		
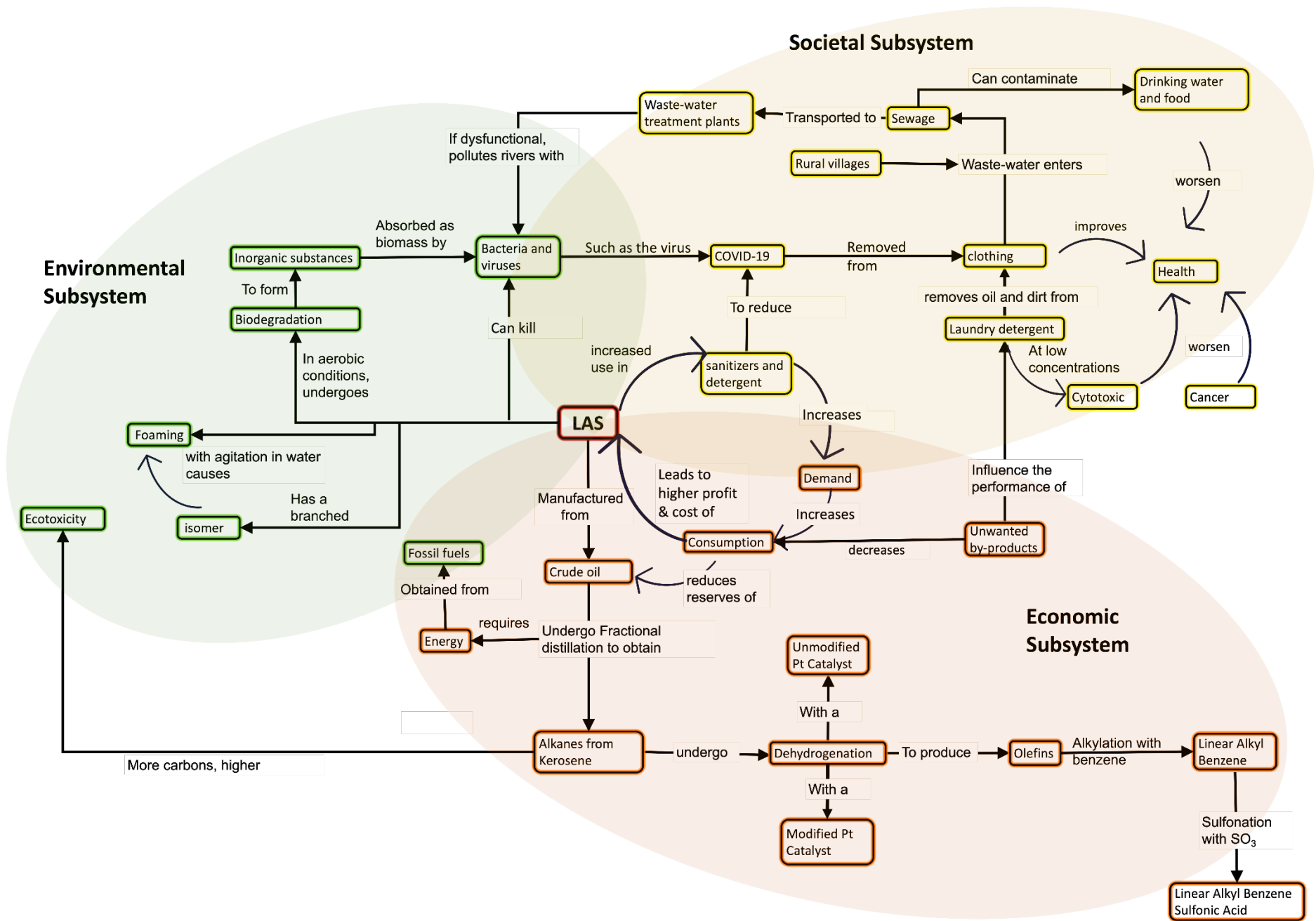
Figure 1: Partial SOCME that formed the starting point for students. Only extensions to this SOCME will be assessed.

Table 3: Short SOCME grading rubric

SOLO levels	Sub level	Description	Total Score	Systems Thinking Skills
Unistructural		**At least one new concept added**	8	**Analysis: elements**
		Scores are given for the added concept (5 marks) and one concept is assessed for its correctness, format, and relevance (3 marks).		New concepts added that are relevant to the system of LAS, which relate to any of the concepts learned in the surfactant lecture
Multi-structural Only assess one sublevel. Earlier levels get full marks.	Low	**2 or 3 concepts without connections**	8	
		Scores are given for the added concepts (5 marks) and all the added concepts are assessed for its correctness, format, and relevance (3 marks) .		
	Medium	**More than 3 concepts without connections**	8	
		Scores are given for the added concepts (5 marks) and all the added concepts are assessed for its correctness, format, and relevance (3 marks).		
	High	**More than 3 concepts with connections**	8	
		Scores are given for the added concepts (5 marks) and all the added concepts are assessed for its correctness, format, and relevance (3 marks).		
Relational Assess all three levels for the SOCME	Low	**Connections between concepts within one or two subsystems**	10	**Analysis: Relationships** Connections made with appropriate linking words within subsystems between concepts
		Scores are given for adding 1-2 valid connections in one or two subsystems (5 marks) and assessing one proposition within one subsystem for its relevance, appropriateness, correctness of the connection, format and whether it can be read as a proposition or feedback loop (5 marks).		
	Medium	**Connections between concepts within all three subsystems**	10	
		Scores are given for all the connections shown in all three subsystems (5 marks) and assessing a different proposition within one subsystem for its relevance, appropriateness, correctness of the connection, format and whether it can be read as a proposition or feedback loop (5 marks).		
	High	**Connections within and between subsystems**	10	**Integration: dynamic interactions** new concepts or linking words that connect between subsystems (change over time can be assessed if explicitly prompted)
		Scores are given for all the connections within and between subsystems (5 marks) and assess all the propositions between subsystems for its relevance, appropriateness, correctness of the connection, format and whether it can be read as a proposition or feedback loop(5 marks).		
Extended abstract Assess organization and application		**Organize concepts into subsystems and add new subsystems**	10	**Integration: Organization** Students were able to fit concepts into their relevant subsystem and indicated new subsystems or added new subsystem boundaries
		Scores are given for the organization of concepts on the SOCME by firstly assessing the organization of one concept (2 marks), then the organization of 2 or 3 concepts (2) then more than 3 concepts without the connections (2 marks) and then more than 3 concepts with their connections (2 marks). This is followed by assessing the relevance of the newly added subsystem with its concepts, linking words and prediction (2 marks)		
		Apply knowledge holistically to make future predictions	8	**Application** If students made predictions with concepts and relationships
		Scores are given for the predictions added (5 marks) and for the propositions to assess if it tells a story about the whole system, for format, clarity and relevance (3 marks)		

Table 4: Full SOCME assessment rubric

SOLO LEVEL	Description	Measure of quality on rubric	Marks	Score per SOLO Level	Systems thinking skills assessed
Pre-structural	No new concepts, linking words, or relevant information were added and SOCME looks like the original provided partial SOCME.	If no new concepts are shown and SOCME looks like the provided SOCME (see appendix A)	0	0	
Unistructural	Mentions at least one relevant piece of information (one new concept)	Give 5 marks if one new concept is shown on the map	5	8	**Analysis: elements** New concepts added that are relevant to the system of LAS, which relate to any of the concepts learned in the surfactant lecture
		Assess **one new concept** on the SOCME and score the following:			
		The word added is a concept and not a linking word	1		
		The new concept added is relevant (relates to surfactants and linear alkyl benzene sulfonate)	1		
		The concept is in the correct format (in a block, appropriate font, size, color)	1		
Multistructural Low	Contains only 2 or 3 new independent relevant concepts, without further elaboration (without linking words and connections)	Give 5 marks for showing only 2-3 new independent relevant concepts	5	8	
		Assess **all the newly added concepts** and score the following:			
		The word added is a concept and not a linking word	1		
		The new concept added is relevant (relates to surfactants and linear alkyl benzene sulfonate)	1		
		The concept is in the correct format (in a block, appropriate font, size, color)	1		
Multistructural Medium	Contains more than 3 new concepts, but is presented in isolation with no (or some) connections or linking words between concepts	Give 5 marks for showing more than 3 new concepts with no (or some) connections	5	8	
		Assess **all the newly added concepts** and score the following			
		The word added is a concept and not a linking word	1		
		The new concept added is relevant (relates to surfactants and linear alkyl benzene sulfonate)	1		
		The concept is in the correct format (in a block, appropriate font, size, color)	1		
Multistructural High	Contains more than 3 concepts with appropriate linking words and connections between concepts	Give 5 marks for showing more than 3 new concepts with connections	5	8	
		Assess **all the newly added concepts** and score the following			
		The word added is a concept and not a linking word	1		
		The new concept added is relevant (relates to surfactants and linear alkyl benzenesulfonate)	1		
		The concept is in the correct format (in a block, appropriate font, size, color)	1		

				10		
Relational Low	Connections are drawn between variables and concepts within one or two subsystems	Give 5 marks for showing at least 1-2 valid connections between concepts within one or more subsystems.	5 marks	10		**Analysis: relationships** Connections made with appropriate linking words within subsystems between concepts
		Assess **a proposition within one subsystem and give** and score the following				
		Relevant connection	1			
		Appropriate linking words	1			
		Connects within the subsystems	1			
		Good format (font, size, color)	1			
		Can be read as a proposition or a feedback loop	1			
Relational Medium	Connections are drawn between variables and concepts within all three subsystems	Give 5 marks for showing connections and concepts within all three subsystems	5 marks	10		
		Assess **a different proposition within one subsystem** and score the following				
		Relevant connection	1			
		Appropriate linking words	1			
		Connects within the subsystems	1			
		Good format (font, size, color)	1			
		Can be read as a proposition or a feedback loop	1			
Relational High	Shows connections within AND between subsystems. (Dynamic relationships might seem static as it is captured in a snapshot of time)	Give 5 marks if connections are **shown within and between** subsystems	5 marks	10		**Integration: dynamic interactions** new concepts or linking words that connect concepts within and between subsystems and that can change over time
		Assess **all propositions between subsystems and give a**				
		Relevant connection	1			
		Appropriate linking words	1			
		Connects between the subsystems	1			
		Good format (font, size, color)	1			
		Can be read as a proposition or a feedback loop	1			
Extended abstract	At the extended abstract level, students can generalize and make predictions and organize systems components to understand the whole system	**Unistructural:**		10		**Integration: organization** Students were able to fit concepts into their relevant subsystem and indicated new subsystems or added new subsystem boundaries
		One new concept fits into the subsystem	1			
		Concepts are well organized in the SOCME	1			
		Multistructural Low				
		2 or 3 concepts fit into the subsystem	1			
		Concepts are well organized in the SOCME	1			
		Multistructural Medium:				
		More than 3 concepts without its connections concepts fit within a particular subsystem	1			
		Concepts are well organized in the SOCME	1			
		Multistructural High and Relational:				
		More than 3 concepts with its connections fit within a particular subsystem	1			
		Concepts are well organized in the SOCME	1			
		The Whole SOCME				
		The new concepts AND subsystems (other than economic, societal, and environmental) added are relevant (relates to LAS)	1			

			Mark		
		The concepts, linking words, connections, and predictions added fit within or between subsystems	1		
		If students chose option A: you can give 5 marks if concepts about fossil fuels, carbon dioxide, global warming, climate change, ocean acidification, acid rain, aquatic life, malaria, etc. are shown on SOCME. If students chose option B: you can give 5 marks if concepts about bad water quality, high concentration, washing in rivers, excessive foaming, blocking of sunlight, aquatic life, water pollution, etc. are shown on SOCME.	5	8	**Application** If students gave new concepts and made connections regarding the predictions given
		Does the whole SOCME have good propositions overall that tell a story about the whole system of LA	1		
		Future prediction is made that shows a clear connection and relevance to LAS	1		
		The format of concepts is correct	1		
		TOTAL SOCME SCORE		80	

Level	Score	FINAL SCORE
Unistructural	/8	
Multistructural	/24	/ 80
Relational	/30	
Extended abstract	/18	

Feedback to the group

Table 5: Possible new concepts and linking words for Application

Environmental subsystem	Societal subsystem	Economic Subsystem
- Chemical Waste - Oil spills - Fossil fuels - Greenhouse gasses - Heavy metals - Wastewater Treatment Plants - Sewage - River quality - Anaerobic conditions - Oxygen - Sunlight (foaming blocks sunlight- decreases oxygen in a river) - Eutrophication	- Health risks - Carcinogenic - Covid-19 - Rural villages - Health problems - Household use - Drinking water - Food - Cytotoxic - Population	- Platinum Exports - Job creation - Demand - Supply - Profits - Platinum reserves - Job creation improves the economic status - Detergent performance - Manufacture .

anaerobic conditions caused by extensive **foaming** reduce the **biodegradability** of LAS due to the **decreased biological oxygen demand** of the river, because of the **blocking of sunlight**- limited oxygen is available for biodegradation and hence LAS **concentration** will persist for longer in river systems, thereby increasing the **ecotoxicity.**

South Africa produces the majority of its energy from **fossil fuels** in coal-fired power stations. High temperatures in fractional distillation require **more energy**- which results in increased burning of fossil fuels. This emits more CO_2 into the atmosphere and can contribute to **global warming** and **ocean acidification.**

Sulfonation uses SO_3 and sulfuric acid which would lead to **acid rain** (SO_3) and **acid spills** into groundwater.

SA has abundant platinum reserves, **jobs are created**, more **exports,** and thus good economic growth, however, **heavy metals** are required to modify catalysts, which can result in environmental **pollution** and **health risks** together with the **carcinogenic** effects of benzene that laboratory scientists and workers in production plants have to work with. On the other hand, modified catalysts increase **olefin yields**, produce **high-performance** detergents as it is selective and therefore **reduce waste**

Using the rubric to assess SOCME diagrams

Analysis: elements
Pre-structural and unistructural

SOLO LEVEL	Description	Measure of quality on rubric	Marks	Level Score
Pre-structural	No new concepts, linking words, or relevant information were added and SOCME looks like the original provided partial SOCME.	If no new concepts are shown and SOCME looks like the provided SOCME (see appendix A)	0	0
Unistructural	Mentions at least one relevant piece of information (one new concept)	Give 5 marks if one new concept is shown on the map	5	8
		Assess **one new concept** on the SOCME and score the following:		
		The word added is a concept and not a linking word	1	
		The new concept added is relevant (relates to surfactants and LAS)	1	
		The concept is in the correct format (in a block, appropriate font, size, color)	1	

- Study the SOCME diagram and if the SOCME is identical to the partial SOCME and no new concepts are present, it is on a pre-structural level. Thus score 0 out of 80

- If at least one relevant concept is added, assess the unistructural level, and award 5 marks.

- Choose any new concept added within a particular subsystem and award 3 marks if the concept is not a linking word, it is relevant and in the correct format.

- Count the scores together to give a score out of 8 for unistructural

- If more than one new concept is present on the SOCME proceed to assess the multistructural level.

Analysis: elements
Multistructural

SOLO LEVEL	Description	Measure of quality on rubric	Marks	
Multistructural Low	Contains only 2 or 3 new independent relevant concepts, without further elaboration (without linking words and connections)	Give 5 marks for showing only 2-3 new independent relevant concepts	5	8
		Assess **all the newly added concepts** and score the following:		
		The word added is a concept and not a linking word	1	
		The new concept added is relevant (relates to surfactants and LAS)	1	
		The concept is in the correct format (in a block, appropriate font, size, color)	1	
Multistructural Medium	Contains more than 3 new concepts, but is presented in isolation with no (or some)	Give 5 marks for showing more than 3 new concepts with no (or some) connections	5	8
		Assess **all the newly added concepts** and score the following		

	connections or linking words between concepts	The word added is a concept and not a linking word	1	
		The new concept added is relevant (relates to surfactants and LAS)	1	
		The concept is in the correct format (in a block, appropriate font, size, color)	1	
Multistructural High	Contains more than 3 concepts with appropriate linking words and connections between concepts	Give 5 marks for showing more than 3 new concepts with connections	5	**8**
		Assess **all the newly added concepts** and score the following		
		At least 3 new concepts are linked to given or new concepts with linking words to form a proposition	1	
		The new concepts added are relevant (relate to surfactants and LAS)	1	
		The concepts are in the correct format (in a block, appropriate font, size, color)	1	

- Study the SOCME and decide whether it is on a multistuctural low, medium, or high based on the sublevel descriptions and only assess the applicable level.

- If the SOCME is on multistructural low, score the level out of 8 based on the quality of all the added concepts and proceed to assess the extended abstract level.

- If the SOCME is on multistructural medium, score the level out of 8 based on the quality of all the added concepts and give full marks for the low level

- If the SOCME is on a multistructural high, score the level out of 8 based on the quality of all the added concepts and give full marks for the low and medium levels

- If the SOCME is on a multistructural high, proceed to assess all the relational levels, low, medium, and high.

Analysis: relationships and integration: dynamic interactions
relational

SOLO LEVEL	Description	Measure of quality on rubric	Marks	Level Score
Relational Low	Connections are drawn between variables and concepts within one or two subsystems	Give 5 marks for showing at least 1-2 valid connections between concepts within one or two subsystems.	5 marks	**10**
		Assess **a proposition within one subsystem** and score the following		
		Relevant connection	1	
		Appropriate linking words	1	
		Connects within the subsystems	1	
		Good format (font, size, color)	1	
		Can be read as a proposition or a feedback loop	1	
Relational Medium		Give 5 marks for showing connections and concepts within all three subsystems	5 marks	**10**

	Connections are drawn between variables and concepts within all three subsystems	Assess **a different proposition within one subsystem** and score the following		
		Relevant connection	1	
		Appropriate linking words	1	
		Connects within the subsystems	1	
		Good format (font, size, color)	1	
		Can be read as a proposition or a feedback loop	1	
Relational High	Shows connections within AND between subsystems as interactions.	Give 5 marks if connections are **shown within and between** subsystems	5 marks	**10**
		Assess **all propositions between subsystems** and score the following		
		Relevant connection	1	
		Appropriate linking words	1	
		Connects between the subsystems	1	
		Good format (font, size, color)	1	
		Can be read as a proposition or a feedback loop	1	

- Award 5 marks for relational low if the SOCME shows at least 1-2 valid connections between concepts within one or two subsystems.

- Choose a proposition (two or more concepts connected with linking words) within a subsystem and assess its quality based on its relevance, its linking words, if connections are within the subsystem, its format, and readability as a proposition or feedback loop for a further 5 marks.

- Proceed to relational medium only if connections are shown within all three subsystems and award a score out of 5 if connections are present in all three subsystems

- Choose a different proposition within one of the subsystems and assess its quality based on its relevance, its linking words, if connections are within the subsystem, its format, and readability as a proposition or feedback loop for a further 5 marks

- Proceed to relational high only if connections are shown within AND between all three subsystems and award a score out of 5 for this.

- Assess all of the propositions between subsystems for their quality based on their relevance, their linking words, if connections are between the subsystem, their format, and readability as a proposition or feedback loop for a further 5 marks

- After assessing each level, proceed to assess the extended abstract level.

Integration: organization
Extended abstract

SOLO LEVEL	Description	Measure of quality on rubric	Marks	Level Score
Extended abstract	At the extended abstract level, students can generalize, make predictions and organize systems components to	**Unistructural:**		**10**
		One new concept fits into the subsystem	1	
		Concepts are well organized in the SOCME	1	
		Multistructural Low		
		2 or 3 concepts fit into the subsystem	1	
		Concepts are well organized in the SOCME	1	

	understand the whole system	**Multistructural Medium:**		
		More than 3 concepts without its connections concepts fit within a particular subsystem	1	
		Concepts are well organized in the SOCME	1	
		Multistructural High and Relational:		
		More than 3 concepts with its connections fit within a particular subsystem	1	
		Concepts are well organized in the SOCME	1	
		The Whole SOCME		
		The new concepts AND subsystems (other than economic, societal, and environmental) added are relevant (relates to LAS)	1	
		The concepts, linking words, connections, and predictions added fit within or between subsystems	1	

- Revisit the concept chosen for assessment at the unistructural level and assess its overall organization out of 2 marks by checking whether it fits into the subsystem and whether the concept is well organized.
- Revisit the concept chosen for assessment in the applicable multistructural levels and assess its overall organization out of 2 marks by checking whether it fits into the subsystem and whether the concept is well organized. Award full marks for the unapplicable levels.
- For organization, assess whether the concepts and new subsystems added are relevant
- For application assess whether the concepts relating to future prediction A or B fit within or between the subsystems indicated.
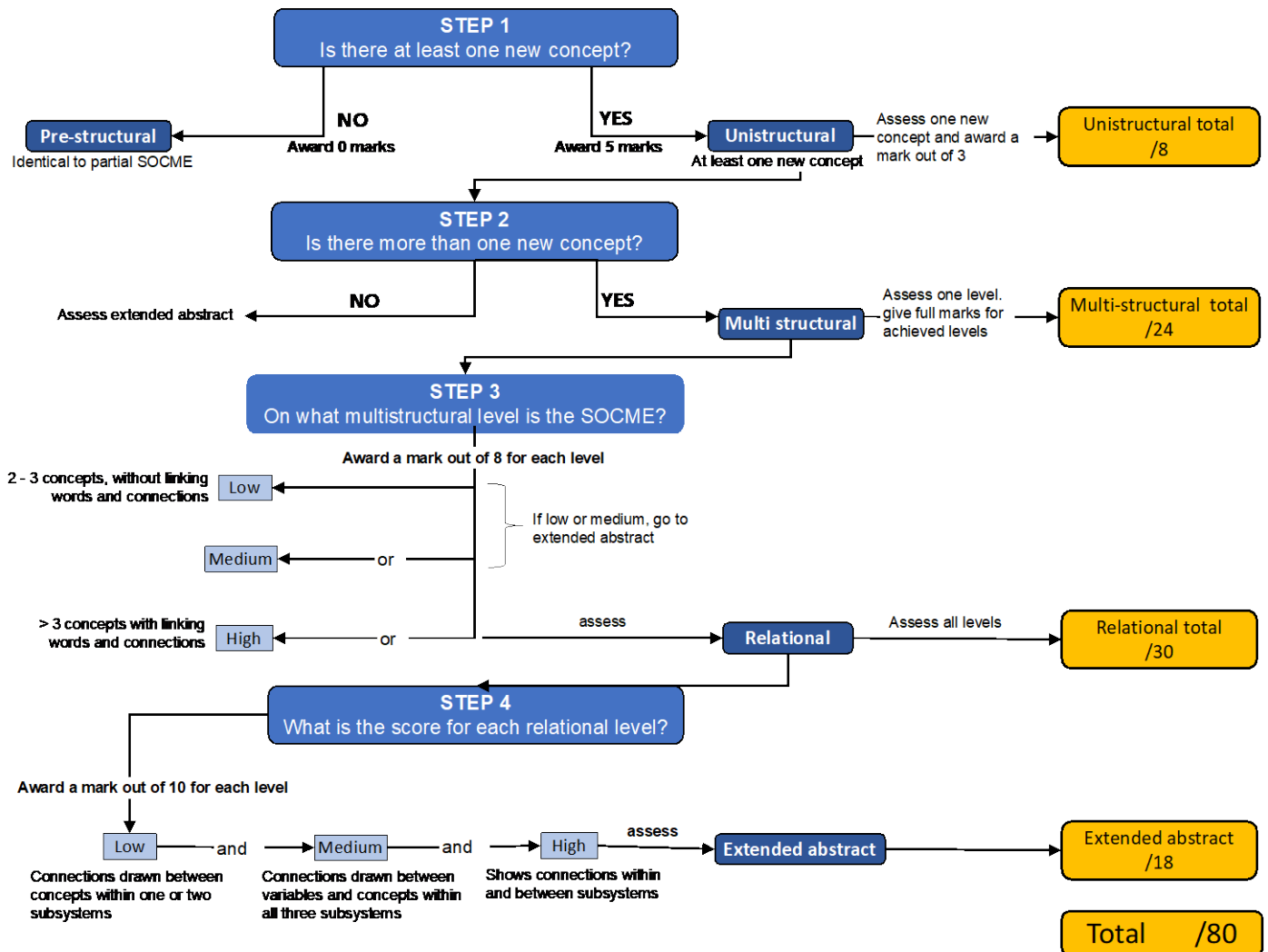
Application
Extended abstract

SOLO LEVEL	Description	Measure of quality on rubric	Marks	Level Score
Extended abstract	At the extended abstract level, students can generalize, make predictions and organize systems components to understand the whole system	If students chose option A: you can give 5 marks if concepts about fossil fuels, carbon dioxide, global warming, climate change, ocean acidification, acid rain, aquatic life, malaria, etc. are shown on SOCME. If students chose option B: you can give 5 marks if concepts about bad water quality, high concentration, washing in rivers, excessive foaming, blocking of sunlight, aquatic life, water pollution, etc. are shown on SOCME.	5	**8**
		Does the whole SOCME have good propositions overall that tell a story about the whole system of LAS	1	
		Future prediction is made that shows a clear connection and relevance to LAS	1	
		The format of concepts is correct	1	

- Study the predictions added to the SOCME diagrams and award 5 marks for any 5 of the concepts listed in the rubric or other relevant concepts.
- Assess whether the propositions tell a story about the whole system of LAS, whether the predictions are clear and relevant and if the format of concepts is correct for another 3 marks.
- Add scores of all the levels together to get a grade out of 80 for the final SOCME diagram.

Summary Flow Chart

assess SOCMEs in 4 steps with 4 questions

STEP 1
Is there at least one new concept?

NO
Award 0 marks

YES
Award 5 marks

Pre-structural
Identical to partial SOCME

Unistructural
At least one new concept

Assess one new concept and award a mark out of 3

Unistructural total /8

STEP 2
Is there more than one new concept?

NO
Assess extended abstract

YES

Multi structural

Assess one level. give full marks for achieved levels

Multi-structural total /24

STEP 3
On what multistructural level is the SOCME?

Award a mark out of 8 for each level

2 - 3 concepts, without linking words and connections — **Low**

Medium — or

If low or medium, go to extended abstract

> 3 concepts with linking words and connections — **High** — or

assess

Relational

Assess all levels

Relational total /30

STEP 4
What is the score for each relational level?

Award a mark out of 10 for each level

Low — and
Connections drawn between concepts within one or two subsystems

Medium — and
Connections drawn between variables and concepts within all three subsystems

High
Shows connections within and between subsystems

assess

Extended abstract

Extended abstract /18

Total   /80

Example SOCME Produced by Home Group 3

The following example SOCME diagram submitted by home group 3 shown on **page 14** was assessed with the rubric descriptions and rules and by using the 4 questions in the flow chart. The partial SOCME was colored in grey in the background so that emphasis can be placed on assessing the newly added concepts and connections. The SOCME grades per each level are provided as an example of how grading was done. Feedback on assessing each level together with the overall levels of complexity and systems thinking skills demonstrated are reported.

Example SOCME Produced by Home Group 3

Home Group 3
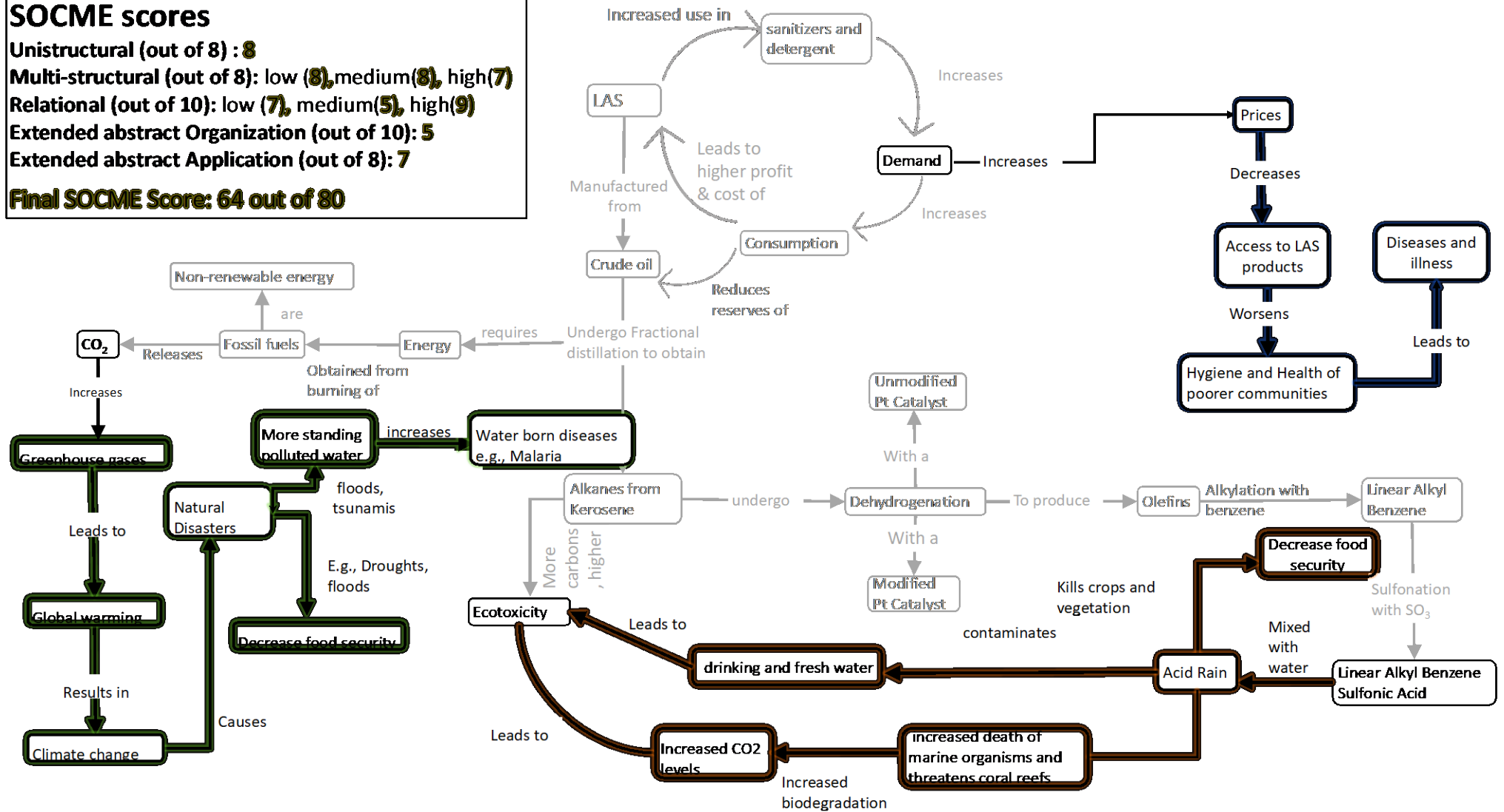**SOCME scores**
Unistructural (out of 8) : 8
Multi-structural (out of 8): low (8), medium(8), high(7)
Relational (out of 10): low (7), medium(5), high(9)
Extended abstract Organization (out of 10): 5
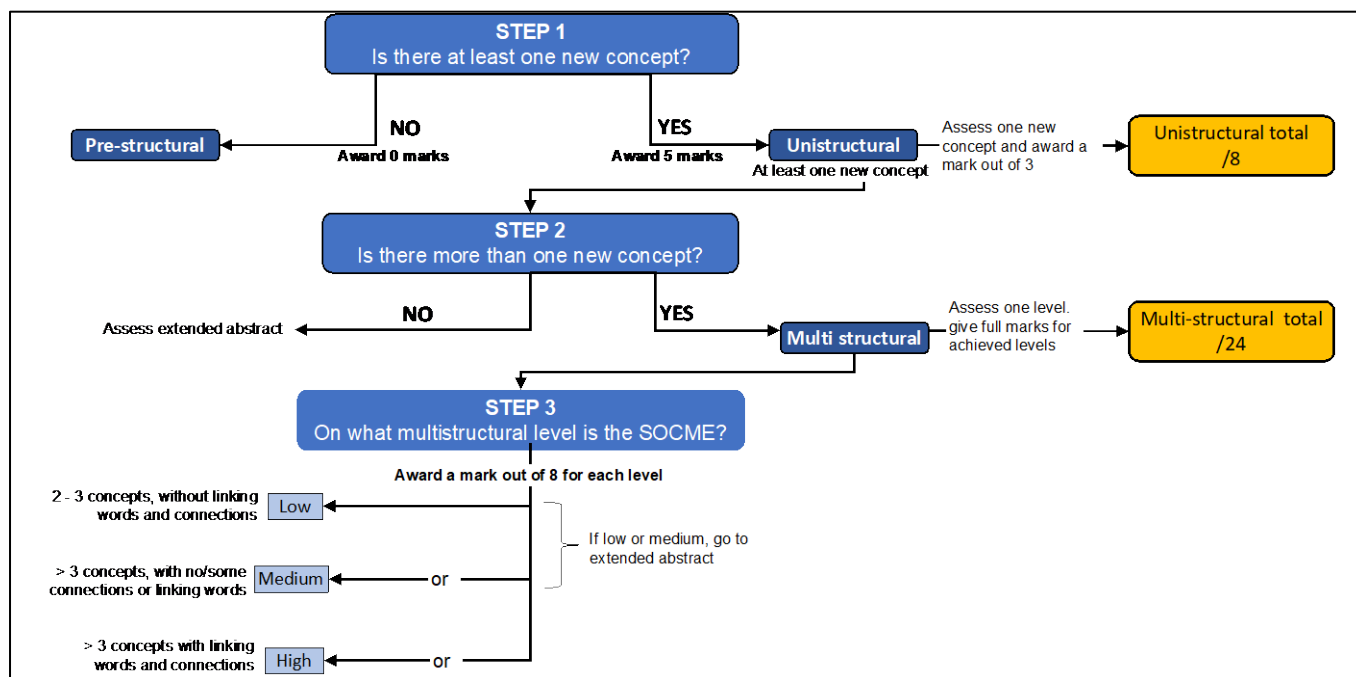Extended abstract Application (out of 8): 7

Final SOCME Score: 64 out of 80

Using the rubric to assess an example SOCME diagram Analysis: elements
Pre-structural, unistructural and multistructural

From studying the example SOCME diagram it is clear that more than one new concept was added to the SOCME, it is therefore not on a pre-structural level and one can proceed to assess the unistructural level. Therefore 5 out of 5 was awarded for showing at least one new concept. In total 16 new concepts were added to the SOCME and a further 3 marks, one of these concepts was randomly chosen to be assessed for unistructural. The concept *"drinking and fresh water"* was chosen and it scored 3 out of 3 as it was a concept, it was relevant to LAS as the acid rain that can potentially result from the sulfonation step in the industrial manufacturing process can contaminate drinking and fresh water. The format was also good as the color was red, and it was in a concept block with appropriate font and size. Therefore a total score of 8 was given out of 8. Since more than one concept is present proceed to assess one of the multistructural levels.

SOLO LEVEL	Description	Measure of quality on rubric	Marks	Level Score
Pre-structural	No new concepts, linking words, or relevant information were added and SOCME looks like the original provided partial SOCME.	If no new concepts are shown and SOCME looks like the provided SOCME (see appendix A)	0	0
Unistructural	Mentions at least one relevant piece of information (one new concept)	Give 5 marks if one new concept is shown on the map	5	8
		Assess **one new concept** on the SOCME and score the following:		8
		The word added is a concept and not a linking word	1	
		The new concept added is relevant (relates to surfactants and LAS)	1	
		The concept is in the correct format (in a block, appropriate font, size, color)	1	

Since the SOCME contains more than 3 concepts with appropriate linking words and connections between concepts, this level is assessed and the SOCME is awarded full marks for multistructural low and medium. 5 marks are awarded for multistructural high since more than 3 concepts are present. Now for an additional 3 marks, the 15 other concepts are all assessed for their quality. At least 3 of the concepts are linked to given or new concepts with linking words to form a proposition therefore 1 mark is awarded here, for example, "*demand increases prices decreases access to LAS products*", the newly added concepts all seem relevant to the system of LAS, thus 1 mark is awarded here. However, the format of all of the concepts is not correct as some concepts contain linking words for example "*decrease food security*", "*increased CO₂ levels*", and "*increased death of marine organisms and threatens coral reefs*" therefore 0 out of 1 for format. Therefore even though many concepts were added, some concepts lacked in quality. Since the SOCME is on the highest multistructutal level, we can proceed to assess all of the relational levels.

SOLO LEVEL	Description	Measure of quality on rubric	Marks	
Multistructural Low	Contains only 2 or 3 new independent relevant concepts, without further elaboration (without linking words and connections)	Give 5 marks for showing only 2-3 new independent relevant concepts	5	**8** 8
		Assess **all the newly added concepts** and score the following:		
		The word added is a concept and not a linking word	1	
		The new concept added is relevant (relates to surfactants and LAS)	1	
		The concept is in the correct format (in a block, appropriate font, size, color)	1	
Multistructural Medium	Contains more than 3 new concepts, but is presented in isolation with no (or some) connections or linking words between concepts	Give 5 marks for showing more than 3 new concepts with no (or some) connections	5	**8** 8
		Assess **all the newly added concepts** and score the following		
		The word added is a concept and not a linking word	1	
		The new concept added is relevant (relates to surfactants and LAS)	1	
		The concept is in the correct format (in a block, appropriate font, size, color)	1	
Multistructural High	Contains more than 3 concepts with appropriate linking words and connections between concepts	Give 5 marks for showing more than 3 new concepts with connections	5	**8** 7
		Assess **all the newly added concepts** and score the following		
		At least 3 new concepts are linked to given or new concepts with linking words to form a proposition	1	
		The new concepts added are relevant (relate to surfactants and LAS)	1	
		The concept are in the correct format (in a block, appropriate font, size, colour)	1 0	

Analysis: relationships and Integration: dynamic interactions
Relational low, medium and high
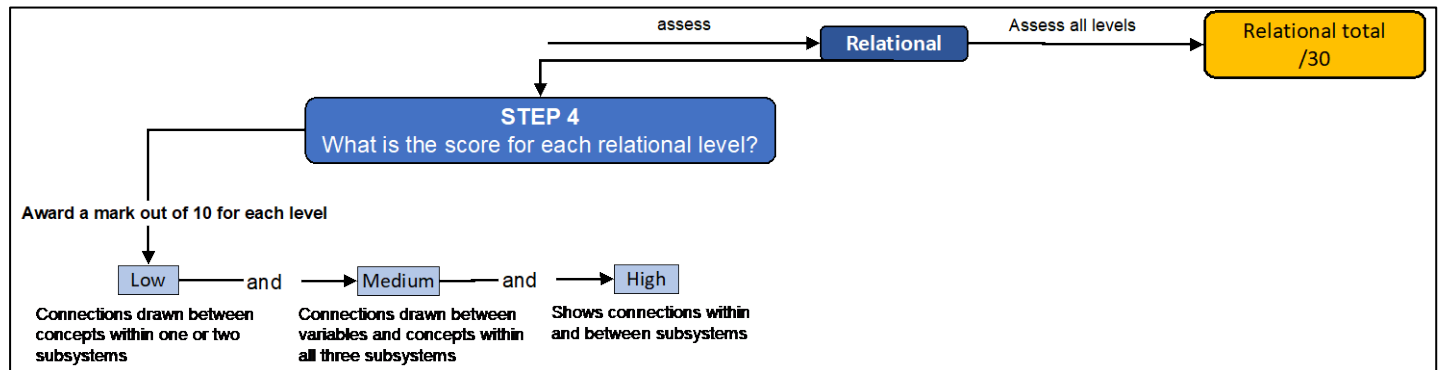
On the SOCME at least 1 or 2 valid connections are shown between concepts within one or two subsystems and therefore 5 marks were given. For a further 5 marks a proposition is chosen within a subsystem to assess its quality. The following proposition "*Linear Alkylbenzene sulfonic acid (LABSA) mixed with water acid rain kills crops and vegetation decrease food security*" chosen was indicated within the economic subsystem. This connection was relevant as sulfonation in the industrial manufacture of LAS could contribute to potential acid rain that can kill crops and vegetation. However, the linking words were not appropriate as LABSA won't result in acid rain if just mixed with water, therefore the quality of linking words used in this proposition was poor. The format of the concepts were good, however it was difficult to read as a proposition and not all the connections were within the economic subsystem. Therefore only 2 marks were given out of 5 and a total of 7 marks were given for relational low.

For relational medium 5 marks 0 out of 5 marks were given for relational medium as connections were not shown in all three subsystems. The only connections shown was in the environmental and economic subsystem. To assess this level for a further 5 marks, a different proposition was chosen in another subsystem to assess its quality. The proposition added to a new subsystem was "*demand increases prices decreases access to LAS products worsens hygiene and health of poorer communities leads to diseases and illness*". The connections in this proposition was relevant, the linking words were appropriate, it connected within the new subsystem, concepts and connections had a good format and it can be read as a position or feedback loop. 5 marks were awarded adding up to a total of 10 out of 10 for relational medium.
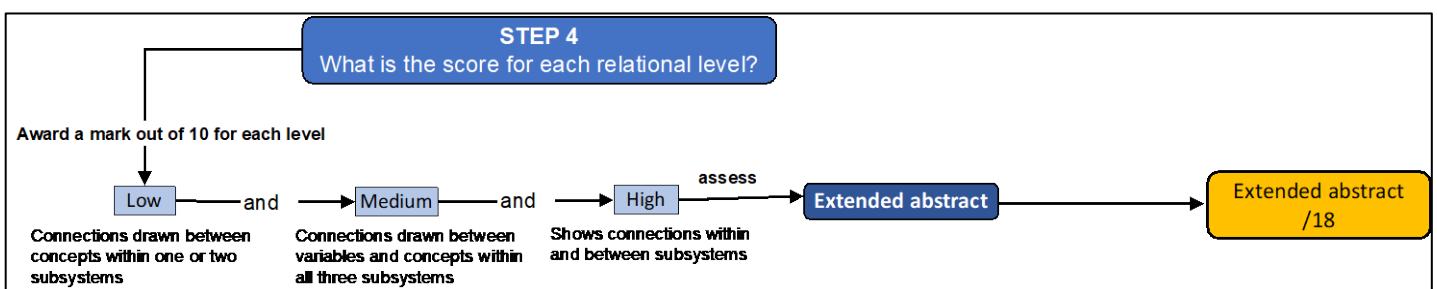
For relational high 5 marks were awarded for connections that were shown between subsystems together with the connections within subsystems. However, for assessing 5 more marks all the propositions between subsystems were assessed as interactions. The following interactions were identified between the economic and environmental subsystem "*acid rain increased death of marine organisms and threatens coral reefs increased biodegradation increased CO_2 levels leads to ecotoxicity*" together with "*acid rain contaminates drinking and fresh water leads to ecotoxicity*" and the economic subsystem with the new subsystem "*demand increases prices decreased access to LAS products worsens hygiene and health of poorer communities leads to diseases and illness*". All of these

interactions seemed relevant, however the linking words between subsystems in two of the three interactions were poor, however connections was between subsystems, had a good format and could be read as a proposition or feedback loop. Therefore a score of 4 out of 5 was given, giving a total of 9 out of 10 for relational high. Overall, connections between concepts within and between subsystems have been made, however, some linking words are not appropriate.

SOLO LEVEL	Description	Measure of quality on rubric	Marks	Level Score
Relational Low	Connections are drawn between variables and concepts within one or two subsystems	Give 5 marks for showing at least 1-2 valid connections between concepts within one or two subsystems.	5 marks	**10** 7
		Assess **a proposition within one subsystem** and score the following		
		Relevant connection	1	
		Appropriate linking words	1 0	
		Connects within the subsystems	1 0	
		Good format (font, size, colour)	1	
		Can be read as a proposition or a feedback loop	1 0	
Relational Medium	Connections are drawn between variables and concepts within all three subsystems	Give 5 marks for showing connections and concepts within all three subsystems	5 0 marks	**10** 5
		Assess **a different proposition within one subsystem** and score the following		
		Relevant connection	1	
		Appropriate linking words	1	
		Connects within the subsystems	1	
		Good format (font, size, colour)	1	
		Can be read as a proposition or a feedback loop	1	
Relational High	Shows connections within AND between subsystems as interactions.	Give 5 marks if connections are **shown within and between** subsystems	5 marks	**10** 9
		Assess **all proposition between subsystems** and score the following		
		Relevant connection	1	
		Appropriate linking words	1 0	
		Connects between the subsystems	1	
		Good format (font, size, colour)	1	
		Can be read as a proposition or a feedback loop	1	

Integration: organization
Extended abstract

STEP 4
What is the score for each relational level?

Award a mark out of 10 for each level

Low — and — Medium — and — High — assess — Extended abstract — Extended abstract /18

Connections drawn between concepts within one or two subsystems

Connections drawn between variables and concepts within all three subsystems

Shows connections within and between subsystems

To assess the organization of concepts and the addition of new subsystem boundaries, some of the organization of concepts chosen to assess this level must be revisited. Recall that the concept *"drinking water and fresh water"* was chosen to assess the unistructural level. It should now be assessed based on whether it fits into the economic subsystem as indicated on the SOCME (since the concept is coloured in orange) and whether it is well organized in the SOCME. This concept did not fit well into the economic subsystem and related more to the environmental subsystem and for that reason it was also not organized well in the SOCME. Since, the SOCME was on a multistructural high level, the scores for multistuctural low and medium for organization got full marks. For the 16 added concepts, only half of the concepts fitted well into their subsystems, specifically referring to the concepts that related to future predictions. These concepts from the proposition "*CO2 increases greenhouse gasses leads to global warming results in climate change causes natural disasters eg floughts droughts decrease food security and floods, tsunamis more standing water increases water borne diseases eg. Malaria*" were organized well into the environmental subsystem. a new subsystem was added with relevant concepts, however the subsystem was not given a name and the concepts within the new subsystem fitted better into existing subsystems, for example *"prices"* fit well into the economic subsystem and *"acces to LAS products", "hygiene of health of poorer communities"* and *"diseases and illness"* fit better into the societal subsystem. Overall the concepts added for the predictions relating to prediction A or B fit well into the environmental subsystem, however other concepts, linking words and connections such as *"acid rain"*, "crops and vegetation" fits better into the environmental subsystem and *"decreased food security"* fits better into the societal subsystem. Therefore concepts could have been better organized into more appropriate subsystems. Therefore a total score of 5 out of 10 was awarded for extended abstract for organization.

SOLO LEVEL	Description	Measure of quality on rubric	Marks	Level Score
Extended abstract	At the extended abstract level, students can generalise, make predictions and organize systems components to understand the whole system	**Unistructural:**		**10**
		One new concept fit into the subsystem	~~1~~ 0	5
		Concept is well organized in the SOCME	~~1~~ 0	
		Multistructural Low:		
		All the newly added concepts fit within a particular subsystem	1	
		Concepts are well organized in the SOCME	1	
		Multistructural Medium:		
		All the newly added concepts fit within a particular subsystem	1	
		Concepts are well organized in the SOCME	1	
		Multistructural High:		
		All the newly added concepts fit within a particular subsystem	~~1~~ 0	
		Concepts are well organized in the SOCME	1	
		The whole SOCME		
		The new concepts AND subsystems (other than economic, societal and environmental) added are relevant (relates to LAS)	~~1~~ 0	
		The concepts, linking words, connections and predictions added fit within or between subsystems	~~1~~ 0	

Application
Extended abstract

Students ability to apply their systems thinking skills to make predictions and to tell a story of LAS through all the concepts, connections, linking words and subsystems added. On this SOCME predictions were added based on the option A provided. The SOCME showed more than 5 concepts that related to this prediction and therefore a score of 5 was given out of 5. For a further 2 marks the SOCME as a whole was assessed on whether the propositions tell a story about LAS, whether the prediction is clear and relevant to LAS and whether the format of concepts are correct. Where the latter was achieved, however the poor quality linking words and lack of organization made it difficult to see the coherent story and interconnectedness of LAS. Students had a good prediction in the environmental subsystem, with good concepts and linking words, however, the overall picture of the SOCME was lacking. Therefore a score of 7 out of 8 was given.

SOLO LEVEL	Description	Measure of quality on rubric	Marks	Level Score
Extended abstract	At the extended abstract level, students can generalise, make predictions and organize systems components to understand the whole system	If students chose option A: you can give 5 marks if concepts about fossil fuels, carbon dioxide, global warming, climate change, ocean acidification, acid rain, aquatic life, malaria etc. are shown on SOCME. If students chose option B: you can give 5 marks if concepts about bad water quality, high concentration, washing in rivers, excessive foaming, blocking of sunlight, aquatic life, water pollution, etc. are shown on SOCME.	5	**8** 7
		Does the whole SOCME have good propositions overall that tell a story about the whole system of LAS	1 0	
		Future prediction is made that shows clear connection and relevance to LAS	1	
		Format of concepts are correct	1	

A summary of the scores per SOLO level and the corresponding systems thinking skill is shown below.

Assessment of SOCME: Home Group 3				
SOLO levels	Sub level	Total per level	Score	Systems thinking skills
Unistructural		8	8,00	Analysis: elements
Multi-structural	Low	8	8,00	
	Medium	8	8,00	
	High	8	7,00	
Relational	Low	10	7,00	Analysis: relationships
	Medium	10	5,00	
	High	10	9,00	Integration: dynamic interactions
Extended abstract	Organization	10	5,00	Integration: organization
	Application	8	7,00	Application
TOTAL SCORE OUT OF 80			**64,00**	

Overall, this SOCME diagram was on a multi- structural high level and a relational high level, with evidence of extended abstract shown, however poor quality especially in some concepts and linking words and in the overall organization of concepts. In terms of systems thinking skills as deduced from the scores taken from averages students achieved 96.88% for analysis: elements, 60% for analysis:relationships, 90% for integration: dynamic

interactions, even though the dynamic nature of interactions were assumed to be static in the SOCME diagram, 50% for extended abstract organization and 87.5% for extended abstract application. Clearly indicating overall the SOCME was on a relational high level and that students could identify relevant concepts in the system and relationships within and especially between subsystems, however lacking in quality of linking words and interactions between each subsystem in the SOCME. Organization of skills into new subsystem boundaries was shown, however concepts weren't distinct from the existing subsystems and felt misplaced. Students were able to make future predictions, however application of systems thinking skills to tell a whole story of LAS with propositions and interconnections were lacking.

Recommendations for using the rubric for assessment

- Use the rubric to get perspective with regards to the skills demonstrated by students on SOCME diagrams
- Use the rubric for low stakes assessment to drive the learning of systems thinking
- Use the rubric for formative assessment and use rater feedback to help identify areas that require future attention in the teaching and assessment of systems thinking
- Using the rubric to assess SOCMEs produced by groups to enable large scale assessment
- Consistency is key to using the rubric reliably between raters, therefore we recommend adequate training in systems thinking skills with SOCME examples as a method to enhance consistency of rating.
- The rubric should not restrict students to be creative, but can be useful to show students so that they know what will be expected from them.

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